

CHARACTERIZATION AND MODELING OF SYNTHETIC JET FLOW FIELDS

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Final Report
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Abstract

The purpose of this research was to develop a neural network-based, lumped deterministic source term (LDST) approximation module for modeling synthetic jets in large-scale CFD calculations. The LDST approximation technique developed by the author and his students was employed. A series of two-dimensional calculations were performed to characterize unsteady single and multiple synthetic jet flow fields. The LDSTs were parameterized for different geometries as well as various flow conditions. These results were then used to train a neural network to approximate the LDSTs over a wide variety of conditions. Results include the successful development of a neural network LDST module for single two-dimensional synthetic jets for different Mach number flows and different jet orifice angles and characterization studies of both single and dual two-dimensional synthetic jets.

Objectives

The goals of the proposed research effort were to characterize, parameterize and model a synthetic jet and to demonstrate the accuracy of the model to include the effects of unsteadiness in a turbulent two-dimensional flow field. The approach taken to achieve these goals is described next.

Approach

The approach taken in this research is described in general below, it will be applied in succession to increasingly complicated systems.

1. The first step for all of the systems under consideration is to demonstrate the efficacy of deterministic source terms for that condition. That is, like the earlier work of Gangwar, Lukovic, Orkwis and Sekar [1], a fully unsteady simulation of the complete flow including the synthetic jet geometry will be performed to create a time average solution. This time average solution will then be used to form the LDST for that case. The LDST will then be imposed in a steady state calculation to demonstrate that it incorporates the unsteady effect of the synthetic jet in the steady primary flow field.
2. Next a series of studies will be performed that will explore the parametric space of the individual synthetic jet, the collaborative influence of the synthetic jet system and the main flow field. This will provide the data to be used in training and testing the neural network based LDST as well as leading to an improved understanding of the flow in question.

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3. Part of the data from Step 2 will then be used to train the neural network based LDST following the procedures outlined by Lukovic, et al. [2].
4. The resultant approximate LDST will then be tested against the remaining data obtained in Step 2. LDST improvements will be incorporated if the accuracy of the approximation is deemed insufficient. The accuracy measure applied is the momentum thickness at a given location.
5. The next level of system or flow field complexity will be incorporated in the NN-LDST module by returning to Step 1.

The complexity of the system discussed in Step 5 increased as follows. Steps 1-4 were applied to each of the following synthetic jet systems in sequence.

1. Single two-dimensional synthetic jet. Exploration of external flow conditions for several orifice angles.
2. Two two-dimensional synthetic jets. Exploration of external flow conditions, extension to several jet phase/spacing combinations. The frequency of the two jets will be fixed for every phase/spacing combination to limit the possible free parameters.
3. Single two-dimensional synthetic jet subject to nonzero pressure gradients. Exploration of external flow conditions.

The range of primary flows used for all cases was the same.

Results

The research project was entitled "Characterization and Modeling of Synthetic Jet Flow Fields." Its modeling goal was to apply the Lukovic et al. neural network deterministic unsteadiness source term technique to synthetic jet flow fields and demonstrate its efficacy for this problem through the creation of several source term models parameterized by important flow field variables. The characterization objective of the project was to perform a series of simulations so as to understand better the important flow field parameters for the design of appropriate networks. While it is the ultimate goal of this research to create a general synthetic jet model, the goal of the current research was to demonstrate that the technique is feasible; hence, a single synthetic jet geometry was chosen for the studies.

Single Synthetic Jet Characterization

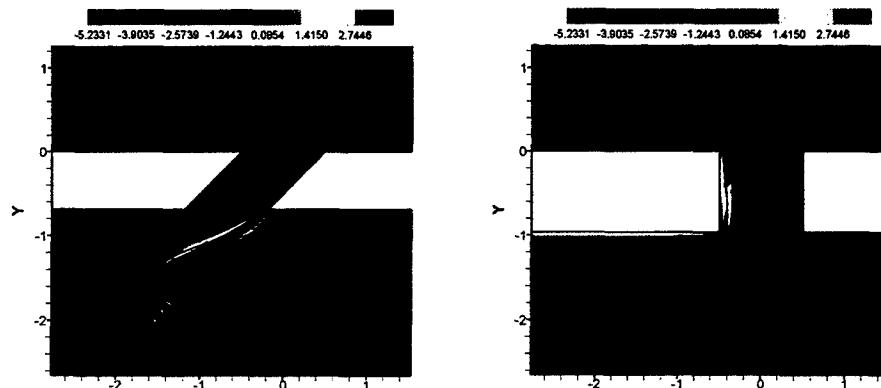


Figure 1 – Instantaneous streamlines of a synthetic jet flow field showing separation off sharp corners.

The initial studies were aimed at understanding the optimal operation of a synthetic jet with a given geometry. The synthetic jet was simulated in two dimensions using the simplest geometric terms possible, a rectangular plenum chamber connected to the main flow through a rectangular orifice. Subsequent jets had different plenum length to depth and studies were made with a range orifice angles relative to the main flow. This probably resulted in less than optimal synthetic jet efficiency because of the sharp corners and associated separated flows, as shown by Figure 1. In addition, the oscillating plenum was modeled by a sinusoidal velocity boundary condition, effectively mimicking a piston of defined stroke as opposed to a vibrating membrane. In all cases the grid was fixed. An initial study was conducted to understand the momentum coefficient one could achieve by varying both the frequency and stroke of the piston. As expected, optimal performance was obtained by driving the device at frequencies corresponding to the Helmholtz resonator. Further studies were performed with the device operating only in its optimal configuration. It should be noted that this simulated device is not based on any available synthetic jet, but rather is a generic device designed to explore the technique.

Lumped Deterministic Source Term Development

Initial testing of the synthetic jet involved its operation in quiescent flow. A series of computations were then conducted over a range of Mach numbers and with a fixed Reynolds number to understand compressibility effects. The results of these unsteady computations were then used to developed their associated LDSTs and demonstrate that their application as the “right hand side” of a steady computation would drive the residual to the time averaged solution, as illustrated in Figure 2. The LDSTs then formed the training base for the first neural network. As indicated previously, taking the set of LDSTs over the entire parametric range and at each grid cell, then rearranging them in a random fashion and using the Levenberg-Marquart method was the approach used to train the source terms for each equation. One quarter of this data was used as testing data and three-quarters as the training data. This becomes an important aspect of the training procedure because of how data is introduced during the training process. One should also note that data from each parametrically different case was used to train the network, although not all of the data from each case was used. In addition, this division of the data should not be confused with the training and testing data shown in Figures 5 and 6. In those cases the “testing data” were not amongst the data used to train or test the network at all, rather they were used to show how well the network predicts cases on which it has not been trained.

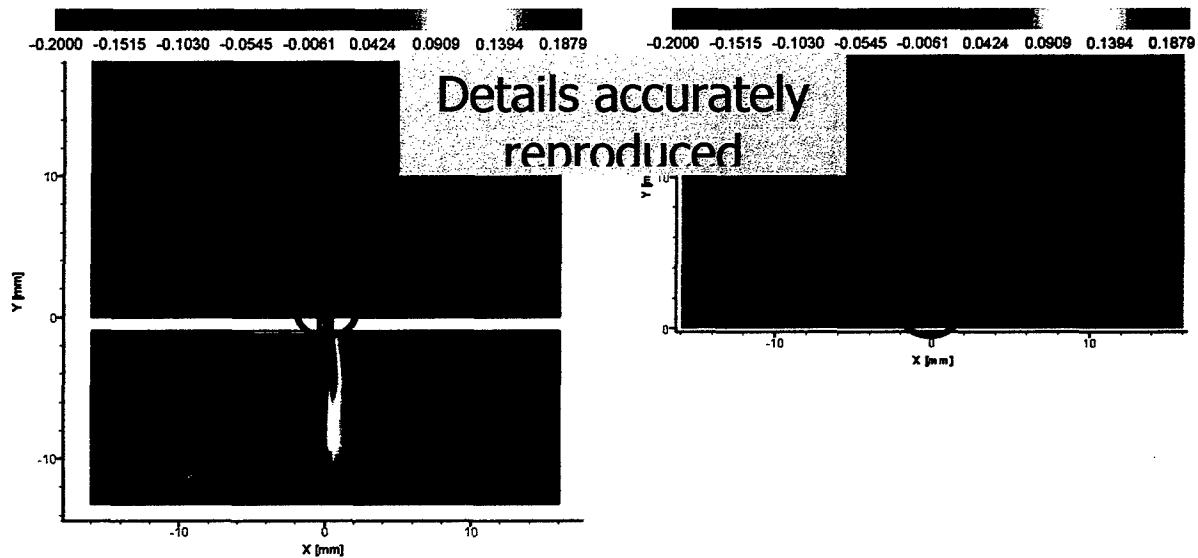


Figure 2 – Vorticity contours obtained from the time average of the unsteady solution (left) and with the LDSTs used to augment a steady solver (right).

Several neural networks were developed in this manner, one each using Mach number, Reynolds number and orifice orientation angle as parameters. The results demonstrated the accuracy of the approach for modeling the time average of the unsteady solution with a steady state solver. Perhaps counterintuitive was the result that these steady computations did not require more time for convergence than steady state cases without source terms, at least for the cases considered. This is extremely encouraging because it demonstrates that the vast time savings (at least two orders of magnitude) inherent in the steady calculations are not lost because of convergence difficulties.

Characterization studies were conducted initially with the assumption that they will be used to understand better how to model the respective flow fields. A first example of this was the results obtained by varying the orifice orientation angle, instantaneous streamlines from which indicated that optimal synthetic jet performance was not being achieved with the more simplistic geometries (see Figure 1). While this is important for the development of useful devices it is not a great concern to the development of the technique. In fact, the odd behavior associated with this event provided a further demonstration of the accuracy of the NN-LDST approach, since it was shown that the technique could capture this phenomenon if it exists in the training data.

Dual Synthetic Jet Characterization

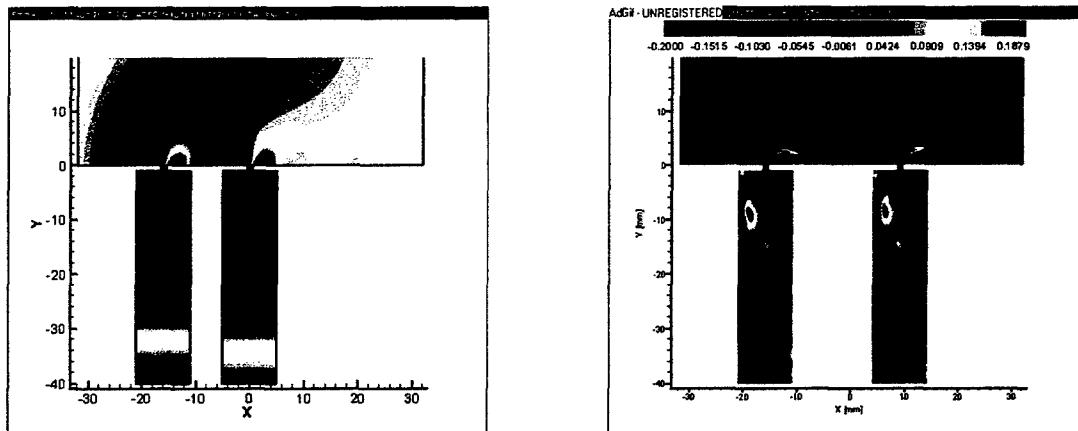


Figure 3 – Pressure (left) and vorticity (right) contours for dual synthetic jets separated by different distances.

The next major characterization study involved the simulation of dual synthetic jets and the effects of oscillation phase shift and jet orifice proximity, as shown in Figure 3. In this case a long thin plenum chamber was used so as to allow very close proximity of the jets. The results indicated that both beneficial and harmful results could be obtained by changing the proximity since significant interactions take place between two jets. Figure 4 shows how the momentum coefficient varies as proximity changes for synchronized phase jets. Note how it changes abruptly for certain proximities. This behavior was found to depend heavily on the local flow interactions and is something of a problem for NN-LDST predictions. However, a smoother set of results can be seen in Figure 5, in which phase shift for a given proximity synthetic jet is shown to either improve or degrade results. In one instance the worst performing proximity case was turned into one of the best performing overall by proper choice of phase shift between the two jets. The interaction results are extremely intriguing and suggest several avenues for future research, including exploring whether the actual and the NN-LDSTs can be made to mimic this effect through their superposition or if an interaction model must be developed to accommodate the effect. More intriguing still is how these interactions change when three-dimensional simulations are performed, since, in addition to the introduction of a second lateral proximity measure as a parameter, one must also properly resolve the three-dimensional flow physics. These issues have been put on hold pending an increase in their priority.

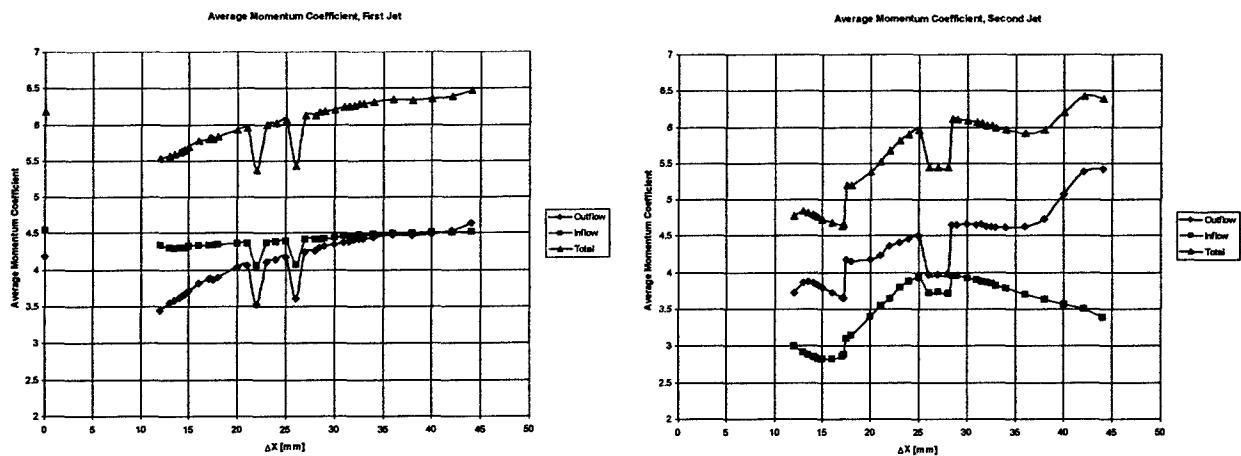


Figure 4 – Momentum coefficient versus proximity for SJ1 (left) and SJ2 (right).

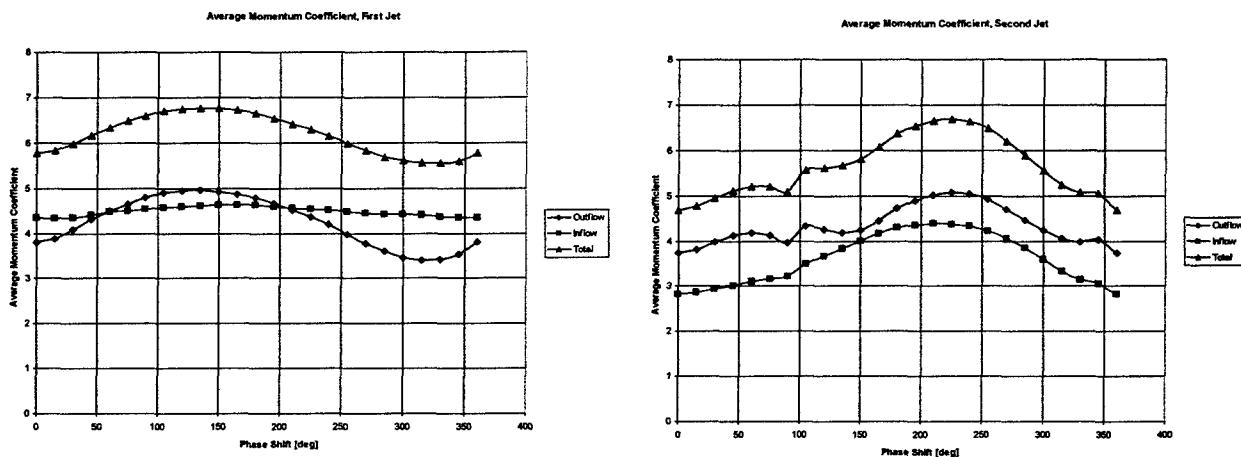


Figure 5 – Momentum coefficient versus phase shift for SJ1 (left) and SJ2 (right).

Characterization of Pressure Gradient

Another major characterization effort involves the necessity of including local pressure gradient amongst the important flow parameters. This study was originally conducted under less than optimal conditions because the available software (CFD++) did not previously have an imposed pressure gradient boundary condition. This problem was avoided after consultation with Hassan Nagib of the University of Illinois, who suggested that pressure gradient studies could be conducted in a manner similar to that performed in low speed wind tunnels. In those cases the walls of the tunnel are altered to achieve a specific pressure gradient, although an iterative procedure is necessary to get a constant pressure gradient. Instead of attempting that optimization, an initial study was made to simply explore a range of pressure gradients similar to that observed in a circular arc

airfoil experiment. This was accomplished by creating an expansion section in the computational domain and adjusting back-pressure to accommodate the same inflow Mach and Reynolds numbers. Solutions obtained with and without a synthetic jet are shown in Figure 6. Unfortunately, the obtained results produced (as anticipated) a non-constant pressure gradient, necessitating interaction with the software manufacturer to supply a more suitable constant pressure gradient option to the code. Results for these initial cases are summarized in the plot of momentum thickness versus average pressure gradient (normalized by total pressure and zero pressure gradient momentum thickness), shown in Figure 7.

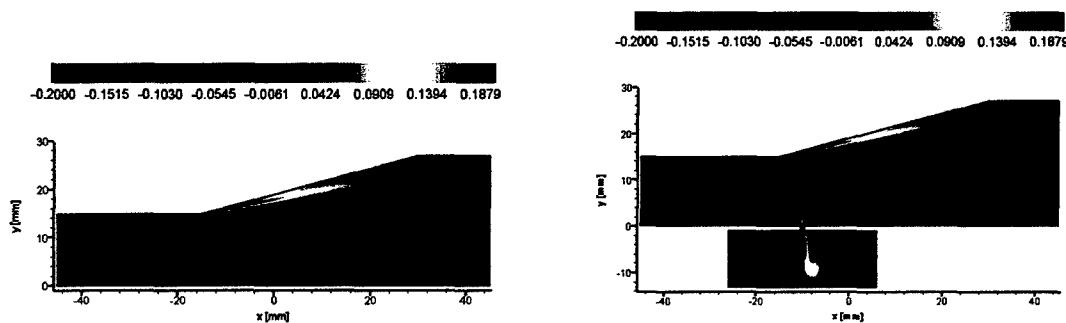


Figure 6 – Vorticity contours for an adverse pressure gradient flow with and without a synthetic jet actuator.

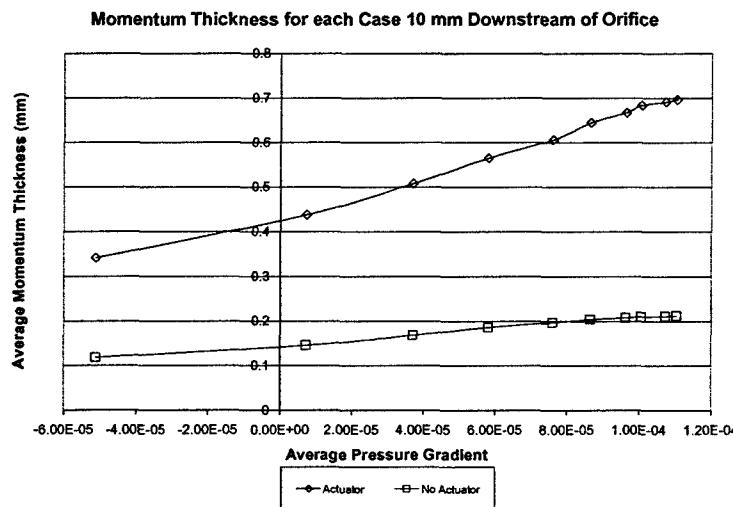


Figure 7 – Momentum thickness 10mm downstream of the jet orifice versus average pressure gradient.

These efforts continued with the defined pressure gradient boundary condition as shown in Figures 8 and 9. To mimic an actual flow the pressure gradient was obtained from a solution of the Langley wall-mounted hump experiment shown in Figure 8. This pressure gradient was then applied in CFD++ to the top wall of a straight channel, results from which are shown in Figure 9.

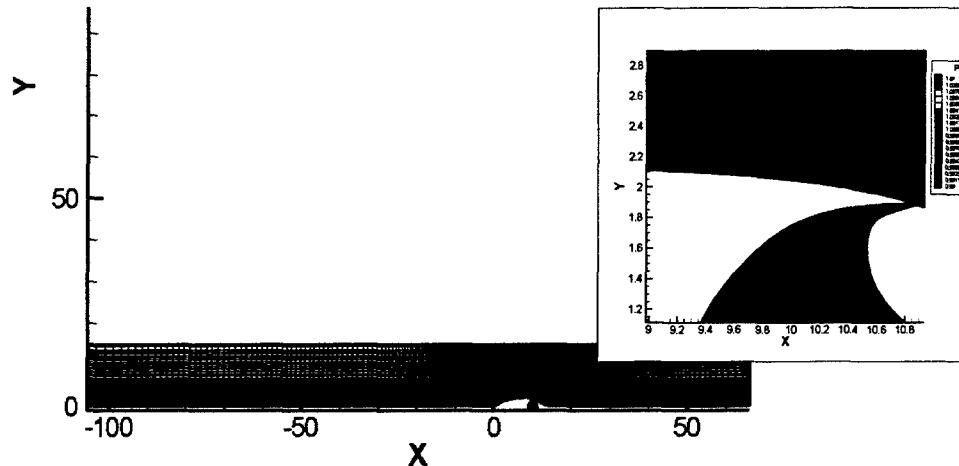


Figure 8 – Grid and flow solution from NASA Langley wall-mounted hump experiment.

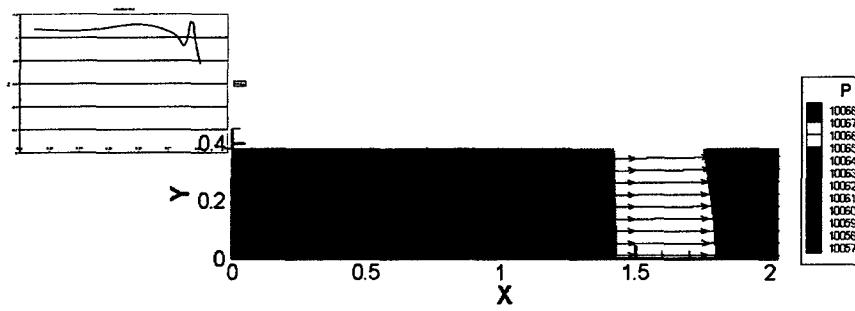


Figure 9 – Pressure contours and prescribed upper wall pressure for straight channel calculation.

Extension to General Grids and Other Solvers

The original neural network development program was extended one year and will be completed by the end of 2005. This effort is directed at two aspects of the NN-LDST problem; the first being a demonstration that the NN-LDST will work on general grids and the second is focused on showing that the NN-LDST can be applied in another code.

The original NN-LDST was developed on a series of identical grids. The LDSTs were thus applicable only to those grids. In the current work the NN-LDST has been retrained with cell volume as a parameter; a simple scaling of the original result. In this way the resultant source term is applicable to any grid. It is important to demonstrate that the source terms are identical (to discretization error and grid resolution) when computed on different grids. Figure 10 shows the source terms on a per unit volume basis developed for a structured grid (left) and an unstructured grid (right). In this case the structured grid resolution is much higher in the orifice region as compared to the unstructured grid, but worse in the main flow. The plot demonstrates that the resultant source terms are identical in form on a per unit volume basis, thus demonstrating that the NN-LDST process is applicable to general grids.

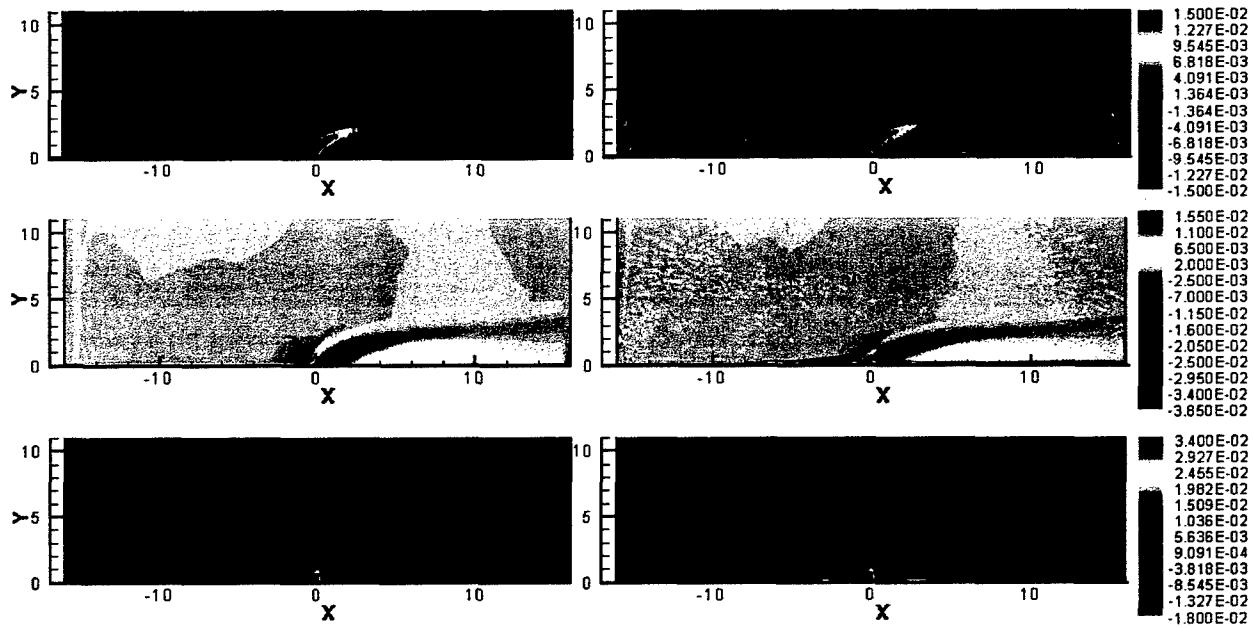


Figure 10 – Momentum (x and y) and energy deterministic source terms from a structured grid (left) and an unstructured grid (right).

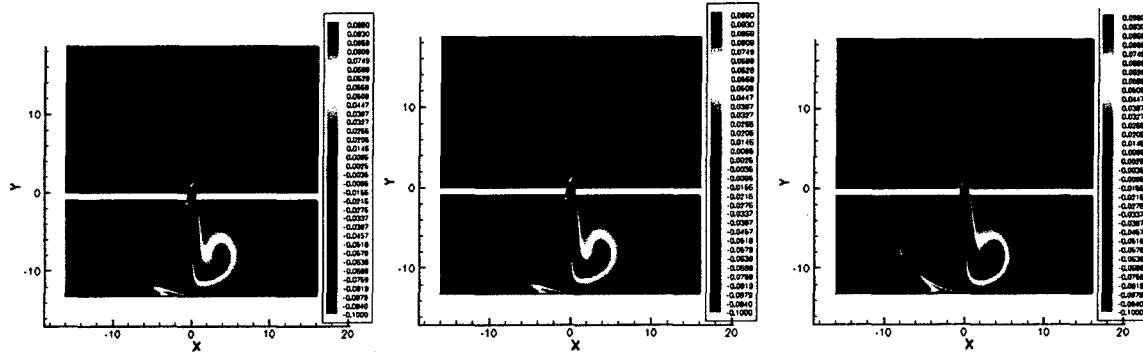


Figure 11 – Vorticity contours obtained from the time averaged unsteady solution (left), the steady solver plus the LDST on the structured grid (center) and the steady solver plus the LDST on the unstructured grid (right).

The next step in this progression was to show that the source terms developed in this manner will provide identical results to grid resolution accuracy. Figure 11 shows main flow results obtained on both a structured and an unstructured grid from the same structured grid derived NN-LDST.

Lastly, the effort is currently exploring the idea of how to include the developed NN-LDSTs in other CFD codes. The question to be answered is whether or not simple mass, momentum, energy and turbulent transport source terms can be properly scaled to accommodate their use in another code. To that end, AFRL and AFOSR researchers suggested the use of an AFRL code, FDL3DI, which is significantly different from

CFD++ and should offer a good test case for comparison, both of the derived source terms and the eventual results. FDL3DI has been acquired from the AFRL and the PI is now in the familiarization phase of the exploratory effort.

The results obtained from the previously supported effort have demonstrated that the NN-LDST is feasible and accurate for modeling synthetic jet flow fields. They have, however, raised some important issues that need to be addressed before this technique can be used to model multiple synthetic jet flow fields. These issues are discussed in the following section.

Summary

A neural network based lumped deterministic source term model was developed for two-dimensional synthetic jets that is capable of modeling the time averaged effect of jet unsteadiness with a steady state solver. Synthetic jet characterization studies were performed to demonstrate the suitability of the solver to reproduce accurately the synthetic jet flow physics. The approach can reproduce accurately the time averaged flow field and flow field properties like the momentum thickness of the resulting boundary layer. The approach can also be used on general grids but has not yet been tested in different solvers. The initial development phase of this technique has been completed and it has been shown to be feasible justifying continued development.

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6. Orkwis, P. and Filz, C., "Characterization of Dual Two Dimensional Synthetic Jets in Cross Flow at Low Mach Number", AIAA Paper 03-3457, 33rd Fluid Dynamics Conference, Orlando, FL, June 2003.

Personnel Supported During Duration of Grant

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Publications

“Modeling of two dimensional synthetic jet unsteadiness using neural network-based deterministic source terms”, M. Pes, B. Lukovic, P.D. Orkwis, and M.G. Turner, AIAA Paper 02-2860, 32nd Fluid Dynamics Conference, St. Louis, MO, June 2002.

“Numerical Analysis of Two Dimensional Directed Synthetic Jets in Cross Flow at Low Mach Number”, D. Lee, P. D. Orkwis, M. G. Turner, C. Filz, M. Pes and N. Caldwell, AIAA Paper 03-0637, 41st Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2003.

“Modeling of Two Dimensional Directed Synthetic Jets Using Neural Network-Based Deterministic Source Terms”, C. Filz, D. Lee, P.D. Orkwis and M. G. Turner, AIAA Paper 03-3456, 33rd Fluid Dynamics Conference, Orlando, FL, June 2003.

“Characterization of Dual Two Dimensional Synthetic Jets in Cross Flow at Low Mach Number”, P. D. Orkwis and C. Filz, AIAA Paper 03-3457, 33rd Fluid Dynamics Conference, Orlando, FL, June 2003.

Honors & Awards Received

AFRL Point of Contact

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- Gave seminar at Wright-Patterson AFB, AFRL/VA on December 12, 2002.
- Met with him at AIAA Aerospace Sciences Meeting in Reno, NV, January 2003.
- Met with him at AIAA Fluid Dynamics Conference in Orlando, FL, June 2003.
- Met with him at AIAA Aerospace Sciences Meeting in Reno, NV, January 2004.
- Met with him at AIAA Flow Control Conference in Portland, OR, June/July 2004.